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Environmental and sustainability evaluation of livestock waste management practices in Cyprus

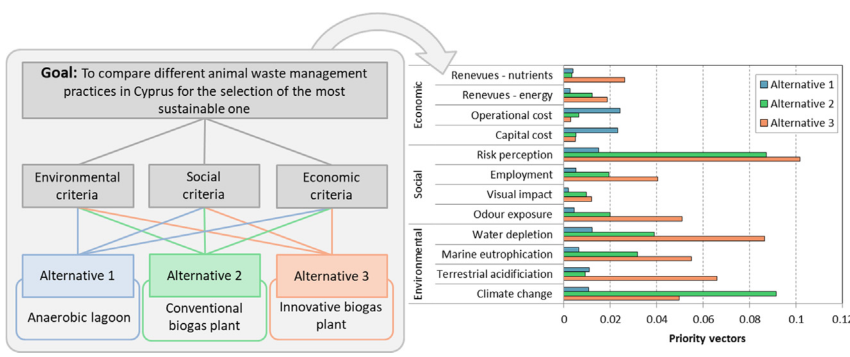
Lucía Lijó [a,*], Nicola Frison [b], Francesco Fatone [b,c], Sara González-García [a], Gumersindo Feijoo [a], Maria Teresa Moreira [a]

[a] Department of Chemical Engineering, Institute of Technology, Universidade de Santiago de Compostela, Spain
[b] Department of Biotechnology, University of Verona, Italy
[c] Department of Materials, Environmental and City Planning Science and Engineering, Faculty of Engineering, Polytechnic University of Marche, Ancona, Italy

HIGHLIGHTS

- Animal waste management practices were compared from a sustainable point of view.
- Different environmental, social and economic indicators were assessed and integrated.
- Life Cycle Analysis and Analytic Hierarchy Process were combined for multi-criteria analysis.
- The environmental performance of alternatives varied according to the impact category studied.
- Resource recovery from animal waste (biogas and biofertilisers) was the most sustainable approach.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this study was to compare the environmental performance and sustainability of different management options for livestock waste in Cyprus. The two most common practices in the country, i.e. the use of anaerobic lagoons and conventional biogas plants, were compared with the innovative scheme developed in the LiveWaste project (LIFE12 ENV/CY/000544), which aims not only to produce bioenergy, but also to treat the digestate for nutrient recovery and water reuse. The Life Cycle Assessment (LCA) methodology was combined with the Analytic Hierarchy Process (AHP) to compare the performance of these alternatives. Four relevant indicators were selected for each dimension of sustainability (environmental, social and economic).
The results of the evaluations showed that anaerobic lagoons are not an appropriate option for the sustainable management of livestock waste due to environmental (e.g. climate change, acidification and eutrophication) and social impacts (e.g. noise exposure, visual impact and risk perception for human health). The most important strengths and weaknesses of anaerobic treatment with and without digestate treatment were identified. Compared to conventional anaerobic digestion where digestate is directly applied as an organic fertiliser, the technology proposed in the project entails higher technological complexity due to nitrogen removal and phosphorus recovery. The rise in chemical and electricity requirements increased the impacts on some indicators, such as

Abbreviations: AHP, Analytic Hierarchy Process; AS, alternative scenario; BTF, biotrickling filter; CC, climate change; CHP, cogeneration heat and power; CR, consistency ratio; CSTR, continuous stirred tank reactor; DF, dark fermentation; FD, fossil depletion; FE, freshwater eutrophication; FU, functional unit; GHG, greenhouse gas; LCA, Life Cycle Assessment; M1, methodology 1; M2, methodology 2; MCA, multi-criteria analysis; ME, marine eutrophication; NVZ, Nitrogen Vulnerable Zone; PROMETHEE, Preference Ranking Organisation Method for Enrichment Evaluations; POF, photochemical oxidant formation; RES, Renewable Energy Sources; SBR, Sequencing batch reactor; TA, terrestrial acidification; TOPSIS, Technique for Order Preference by Similarity to Ideal Solution; TVS, total volatile solids; VOC, volatile organic compound; WD, water depletion.

* Corresponding author.
E-mail address: lucia.lijo@usc.es. (L. Lijó).

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climate change and operational cost (emissions of greenhouse gases and operation costs were around 50% higher), while reduced impacts in others due to proper nutrient management, as acidification and eutrophication impacts (which were 10 and almost two times lower, respectively).
For the specific Cypriot conditions, where the overapplication of nutrients leads to pollution of water bodies, the innovative treatment scheme with higher technological development presents an interesting approach. Nevertheless, the treatment of the digestate should be analysed taking into account the specific characteristics of each scenario.

1. Introduction

Livestock management is a major global environmental problem, with significant impacts to air, water and soil as well as to biodiversity, as explained in the FAO report "Livestock's long shadow" (FAO, 2006). It is estimated that in Europe manure management contributes with 65% to the total anthropogenic ammonia, 40% of nitrogen oxide and 10% of methane; in addition to direct nitrogen and phosphorus emissions to soil and water (Hou et al., 2017; Oenema et al., 2007). These burdens are directly related to outstanding environmental problems such as climate change, acidification and eutrophication. These environmental impacts have increased in recent years, particularly as a result of the current growing trends of intensification and specialisation in livestock production (Oenema et al., 2007). This problem is particularly relevant in Cyprus, where the introduction of intensive farming operations in recent decades has increased the amount of animal waste generated in specific areas, further aggravated by the insular nature of the country (Insam et al., 2014). More specifically, in this country animal waste represents 60% of biodegradable waste, 82% of which is piggery waste (Theofanous et al., 2014). According to Longo et al. (2016), the total production of livestock waste in Cyprus in 2013 was 1.6 million of tonnes of waste. Due to the large volumes of waste produced, it is not possible to apply it as organic fertiliser on the soil. To deal with its management, most small-scale pig and cattle farms use open evaporation lagoons for the management of their animal waste (Kythreotou et al., 2012). In this type of treatment manure is sent to anaerobic lagoons, where the organic material is decomposed under anaerobic conditions, causing uncontrolled emissions of greenhouse gases (GHG) (i.e. methane, nitrous oxide) and other substances such as ammonia to the atmosphere (Kythreotou et al., 2012).

Nevertheless, the number of biogas plants treating animal waste in Cyprus has increased in recent years to 11 units, which is attributed to the promotion of anaerobic digestion as a way to reduce environmental impacts and produce energy and biofertiliser from the digestate (Al Seadi et al., 2013). The production of renewable energy from organic waste is particularly desirable in Cyprus due to the characteristics of its electricity mix. Without interconnections of oil, gas or electricity, Cyprus has a completely isolated energy system, which is totally dependent on imported oil, contributing to 96% of the total primary energy supply (Theofanous et al., 2014).

Taking into account international environmental policies focused on the promotion of renewable energy consumption and the increasing prices of fossil fuels, the need to encourage Renewable Energy Sources (RES) in the current Cypriot energy system is becoming imperative. As a result, in recent years many RES production units have been installed in Cyprus (Theofanous et al., 2014). In 2013, 15% of RES was produced from photovoltaic systems, 75% from wind parks and 11% from biomass-biogas production units (Cyprus Energy Regulatory Authority, 2013).

Regarding the digestate produced by anaerobic digestion, it can be used with any further treatment other than storage during the spread season (Crolla et al., 2013). The storage, transport, handling and application of raw digestate as organic fertiliser imply significant costs for farmers, higher than its fertiliser value due to its large volume and low dry matter content (Rehl and Müller, 2011). The further treatment of the digestate can also contribute to compliance with the specifications laid down in the Nitrates Directive (EEC, 1991) since Nitrogen Vulnerable Zones (NVZs) have been designated in Cyprus as a result of their high concentrations of nitrates in water. In this context, it is becoming crucial to develop innovative treatment schemes which, in line with the concept of circular economy, allow valuable products to be recovered from animal waste, such as renewable energy, nutrients and water. With this idea the LiveWaste project (LIFE12 ENV/CY/000544) was developed in Cyprus, co-financed by LIFE+ EU financial instrument in the thematic area of LIFE+ Environmental Policy and Governance in the priority area of Waste and Natural Resources. The project aimed to develop, demonstrate, optimise and evaluate an innovative combined system for the treatment of livestock waste with the aim of producing renewable energy, a reusable effluent, compost and struvite. Accordingly, the proposed treatment scheme addresses several environmental issues that not only Cyprus, but also other Mediterranean countries are facing today: i) livestock waste management, ii) renewable energy production, iii) water reclamation and iv) nutrients recovery.

As concluded in Martinez et al. (2009), to convert livestock waste treatment systems into sustainable processes, it is necessary to develop new methods that follow the principles of circular economy, shifting to a vision of recycling, including techniques that allow nutrient recovery. Before the implementation of these large-scale innovative systems, it is important to assess their potential environmental and sustainability performance (Hou et al., 2017). In this regard, the Life Cycle Assessment (LCA) is a generally accepted methodology which allows the environmental assessment of the proposed innovations before they reach full scale to anticipate possible problems and related solutions (Mininni et al., 2015).

This methodology has been widely applied to analyse the environmental performance and sustainability of several systems, including waste management technologies. Paccanelli et al. (2015) compared different nitrogen removal options for digestate from an environmental point of view: i) short-cut nitrification/denitrification and ii) partial nitrification and anammox. Prapaspongsa et al. (2010) also evaluated the environmental consequences of 12 combinations of different options of storage, processing and application for pig manure. Eriksson et al. (2016) also performed the LCA of horse manure treatment, including anaerobic digestion, aerobic composting and incineration. De Vries et al. (2012) conducted a comprehensive LCA study on pig manure processing to produce bioenergy and a mineral concentrate. Beyond environmental analysis, other studies included the assessment of other pillars of sustainability, such as social and economic impacts. For example, den Boer et al. (2007) developed a methodology for the environmental, social and economic assessment of waste management systems in regions with rapidly growing economies. In some cases, the outputs of these studies are difficult to interpret because, due to the wide range of indicators, there may not be one fully satisfactory alternative (Angelo et al., 2017). Multi-Criteria Analysis (MCA) is an useful approach to decision-making when different indicators with different results can be obtained in the same framework (Angelo et al., 2017).

Combining LCA with MCA can be an interesting approach to implement LCA outcomes as environmental indicators. In this way environmental criteria can be integrated with social and economic criteria in a holistic way, analysing the sustainability performance of the system. In the available literature, different MCA methodologies have been

applied to several systems, including waste management. For example, Arikan et al. (2017) and Coban et al. (2018) analysed several solid waste disposal options in Turkey applying different MCD methods: i) Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) and Fuzzy TOPSIS. Vučijak et al. (2016) and Milutinović et al. (2014) opted for the Analytic Hierarchy Process (AHP) to determine the preferred waste management model.

The AHP was developed by Saaty (1980) as an alternative multi-criteria assessment methodology. This methodology is designed to structure a decision process in a scenario affected by multiple independent factors, allowing decision makers to efficiently address problems related to relevant criteria and sub-criteria (Bottero et al., 2011). The analysis is based on three fundamental principles: i) breaking down the problem; ii) pairwise comparison of the various alternatives; iii) synthesis of the preferences (Bottero et al., 2011). This methodology was the one selected in this study to be combined with LCA since it is a simple method able to identify the best option based on the integration of criteria of different nature (Chatzimouratidis and Pilavachi, 2009), including quantitative and qualitative indicators reflecting environmental, economic and social performance. According to Bottero et al. (2011), this methodology does not need accurate measurements and indicators, but they use general understanding and informed knowledge. In fact, the AHP is currently one of the most used methods for obtaining criteria weights in MCA from a large amount of heterogeneous data. With particular attention to waste management systems, this method was also successfully applied by Vizzari and Modica (2013) to select the most sustainable approach to pig manure management among nitrogen removal, composting, anaerobic treatment and separation. Moreover, AHP was also used in other studies to identify the best management scheme for different waste streams (Bottero et al., 2011; Molinos-Senante et al., 2014; Samah et al., 2010). LCA and AHP methods have been successfully combined in other assessments, as in Contreras et al. (2008), with the aim of analysing the preferences of stakeholders in municipal solid waste management. However, to the best of our knowledge, they have not been previously applied to select the best solution of livestock waste management.

The objective of this study is to combine two relevant methodologies, LCA and AHP, with the aim of integrating environmental, social and economic indicators into the selection of the most sustainable practices for livestock waste management in Cyprus. The options analysed included the two most common livestock waste management practices in Cyprus: anaerobic lagoons and biogas plants, as well as an innovative treatment scheme for the recovery of various marketable products, as proposed in the LiveWaste project.

2. Materials and methods

2.1. Definition of alternative treatments under study

Traditionally animal production in Cyprus was characterised by small farms scattered around the island. Within this farming approach, the amount of livestock waste produced was limited and could be spread over agricultural land. However, in the last two decades, the shift to intensive animal production has made livestock waste management one of the major pressures on the environment. The aim of this study is to select the most sustainable option for the management of livestock waste in Cyprus. With this purpose, the two most common practices for animal waste management in Cyprus and the one proposed in the LiveWaste project were analysed and compared.

- **Alternative 1 – Anaerobic lagoon**

In this alternative, animal waste is separated into liquid and solid fractions using a centrifuge. The liquid fraction is pumped into an anaerobic lagoon, where it remains until water evaporates. Once a year, sludge is collected from the bottom of the lagoon and applied to soil as organic fertiliser. The typical dimension of the aerobic lagoon in Cyprus is about 5.000 m^2, with a depth ranging from 1 to 3 m, holding about 10,000 m^3 of animal waste. The solid fraction produced after separation is stored in piles for 6 months until the spreading season, when it can be used as organic fertiliser.

- **Alternative 2 – Conventional biogas plant**

Currently, there are about 11 plants operating in Cyprus for biogas production located near farms to reduce transport distances. Among other substrates, they digest pig, cattle and poultry manure, representing about 16% of the animal waste produced in the island. In this alternative, animal waste is treated on-farm in an anaerobic reactor where biogas and digestate are co-produced. Animal waste is pumped into the digester through pipelines to the single-stage digestion process in a continuous stirred tank reactor (CSTR), operated at mesophilic temperature (~37 °C). The produced biogas is filtered and dehumidified. Biogas is used in the cogeneration heat and power (CHP) unit for generating electricity and heat. The electricity produced is fed into the grid, while the heat produced is used to maintain the temperature of the digesters. Regarding digestate management, it should be noted that some plants are equipped with a sequencing batch reactor (SBR) for removing nitrogen from the liquid fraction of the digestate; however, most of them use the reactor as a simple storage tank. In this alternative it has been considered the simple option, where the digestate is stored directly until it can be used as organic fertiliser.

- **Alternative 3 – LiveWaste treatment plant**

In this alternative, a full-scale plant operating under the principles of the LiveWaste project is considered. It includes the anaerobic digestion of the animal waste as the core process, as well as the treatment of all the gaseous, liquid and solid flows.

Anaerobic digestion is the first treatment step and is carried out in two separate tanks. The objective is to perform the hydrolysis and acidogenesis of the organic matter in the dark fermentation (DF) unit and the acetogenesis and methanogenesis in another separate tank where methane is produced (Guo et al., 2010). Both tanks are CSTR operating at different operational conditions under mesophilic conditions (~37 °C). Given that it is necessary to have a biogas with adequate characteristics to ensure efficient and clean bioenergy production, it is necessary to eliminate hydrogen sulphide present in the biogas produced due to its toxic and corrosive characteristics (Abatzoglou and Boivin, 2009). Biological desulphurisation was performed in a biotrickling filter (BTF). The BTF is adapted to anoxic conditions, which accomplishes the oxidation of hydrogen sulphide through the biochemical pathway known as autotrophic denitrification. As a result, BTF removes up to 75% of the hydrogen sulphide contained in the biogas.

The highly diluted digestate with 4–5% of total solids is separated into liquid and solid fractions. The filtration system consists of two elements: a filter bag and an ultrafiltration membrane. A polyelectrolyte is mixed with the digestate before filtration to promote aggregate formation and improve separation capacity. The treatment of the produced permeate consists of a struvite crystalliser and an SBR. The interest of struvite precipitation relies on the potential for nutrient recovery from organic waste streams and the use of this material as slow release fertiliser (Zhang et al., 2010). It is a physico-chemical process in which nitrogen and phosphorus are recovered as struvite crystals ($MgNH_4PO_4 \cdot 6H_2O$). In this case, the process requires the addition of magnesium. The resulting effluent can be also sent to the SBR for the removal of the remaining nutrients to achieve a quality effluent, suitable for its reuse as irrigation water. In the SBR, biological nutrient removal

via nitrite is performed. Each cycle alternates different anaerobic, aerobic and anoxic phases. It is important to highlight the need to add an external carbon source such as acetic acid, since some of the bacteria governing this process are heterotrophic microorganisms.

The composting unit is included to treat all the produced sludge throughout the process. The main objective of this stage is the maturation of this solid fraction to obtain high-quality marketable compost. Thus, the produced sludge treated is mixed with straw to improve its C/N ratio and aeration.

In order to minimise the emissions of volatile organic compounds (VOCs) and odours, the gaseous streams produced during the composting process, as well as those collected from the headspace of the different tanks, were treated in the hybrid biofiltration unit. This method consists of a conventional biofilter coupled with a post-treatment of activated carbon as a polishing step. The use of the activated carbon allows for high efficiency of odour and VOC removal, even if the biofilter does not function properly.

2.2. Environmental assessment methodology

The objective of the LCA conducted is to quantify the environmental impacts associated with the most common practices for the treatment of livestock waste in Cyprus, as well as the system proposed in the LiveWaste project. The common function of the systems under analysis is the treatment of animal waste; therefore, the functional unit (FU) selected was 1 t of animal waste treated.

As shown in Fig. 1, the system boundaries included all the processes involved in each treatment scheme. The production of animal waste

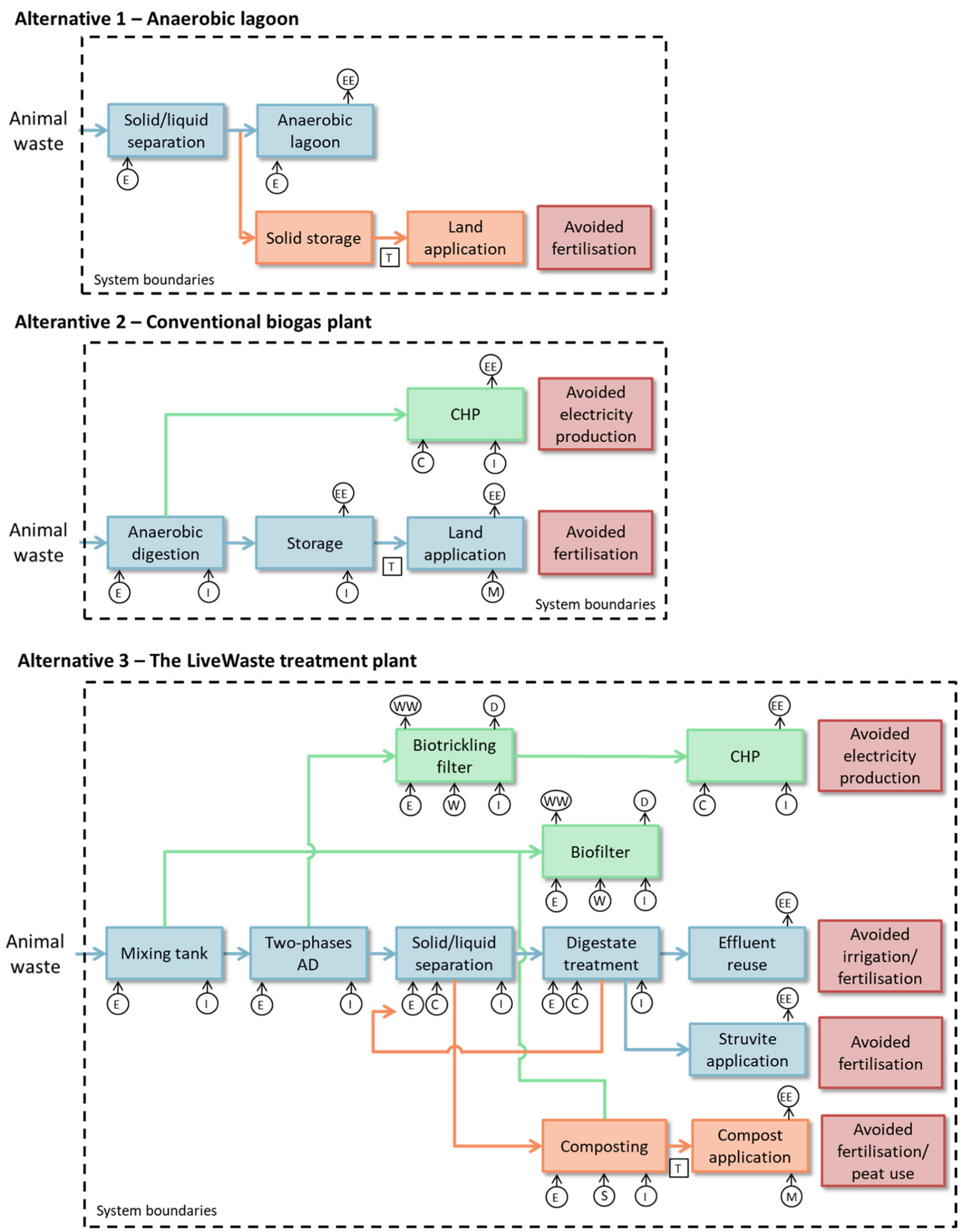

Fig. 1. Unit processes included in the system boundaries for each alternative under study. Acronyms: C = chemicals; E = electricity; EE = emissions; I = infrastructure; L = disposal of waste; M = Machinery; S = Straw; T = transport; W = water; WW = wastewater production.

was excluded from the system boundaries, since its production was considered not to be affected by its treatment route. Some of the alternatives under study are capable of producing valuable products from manure, such as bioenergy and organic fertilisers. To deal with multifunctionality, a system expansion was performed in this study to account for the environmental benefits of producing these products, as they can reduce the need to produce other products with identical function. Therefore, the boundaries of the system under study were extended to include the production and use of these substituted processes. It has been previously demonstrated that the choice of the avoided functions may have a decisive influence on the results (Finnveden et al., 2005).

The potential environmental impacts produced by these three alternative scenarios can be reported in terms of several impact categories of the ReCiPe Midpoint H methodology (Goedkoop et al., 2009). Among the impact categories offered in the methodology, those with greater relevance for these treatment systems under study are climate change (CC) to measure the contribution to the greenhouse effect; photochemical oxidant formation (POF) as a measure of the formation of reactive chemical compounds; fossil depletion (FD) for the reduction of fossil resources; terrestrial acidification (TA) as an indicator of the influence of the acid rain phenomenon; freshwater eutrophication (FE) to quantify the potential nutrient enrichment in surface water and marine eutrophication (ME) to analyse nutrient enrichment of marine water and water depletion (WD) to quantify water consumption.

For each alternative, a life cycle inventory was built that includes all the inputs (i.e., use of resources, raw materials and products, energy carriers, etc.) and outputs (i.e., emissions to air, water and soil, as well as waste and by-products) related to each of the unitary processes defined within the system boundaries of each alternative. The data needed to evaluate the selected indicators were collected during the development of the LiveWaste project.

To perform the LCA study, primary data were collected in Cyprus to better reflect the real situation under study, including data on anaerobic lagoons and biogas anaerobic digestion plants. Subsequently, mass balances were developed for each system, allowing the entire treatment scheme to be modelled. The solid/liquid separation of manure and digestate was modelled according to Bauer et al. (2009). The production of biogas, in terms of total volatile solids (TVS), in Alternatives 2 and 3 was considered as 0.42 m^3 biogas/kg TVS_{fed}, with 60% methane. The CHP for electricity production from biogas had electrical and thermal efficiencies of 35% and 50%, respectively. Direct emissions of methane, nitrous oxide, ammonia and nitrogen oxides from anaerobic lagoons, liquid and solid storage and land application (organic and mineral fertilisers) were accounted for according to the methodology proposed by the IPCC (2006).

Secondary data on the production of chemicals, mineral fertilisers, lubricant oil, transport services, biogas plant infrastructure, agricultural machinery and implements were taken from the ecoinvent® database. The Cypriot electricity profile was modelled using the average electricity production and import/export data for Cyprus in 2013. The four environmental indicators were calculated by converting the inventory data into potential environmental impacts using the characterisation factors provided by the ReCiPe Midpoint methodology (Goedkoop et al., 2009). The summary of the inventory data gathered for the LCA study is presented in Table 1.

Table 1
Inventory data of the three alternatives under study.

	Units	Alternative 1	Alternative 2	Alternative 3
Inputs from technosphere				
Materials, transport and energy				
Livestock waste	t	1	1	1
Polymer	kg			10.8
Sodium hypochlorite	g			0.30
Magnesium oxide	kg			0.28
Acetic acid	kg			2.36
Tractor	kg	0.009	0.03	
Agricultural implement	kg	0.03	0.06	
Diesel	kg	0.08	0.21	
Tractor and trailer	t·km	3.72	24.2	
Electricity	kWh	1.10	2.76	6.40
Inputs from nature				
Avoided resources				
Water	L			789
Outputs to technosphere				
Products				
Energy	kWh		53.9	53.9
Digestate	t		0.97	
Reusable effluent	L			789
Compost	kg			118
Struvite	kg			1.13
Avoided products production				
Nitrogen fertiliser	kg	0.26	0.84	0.51
Phosphorus fertiliser	kg	0.63	1.06	1.34
Electricity	kg		53.9	53.9
Peat	kg			94.2
Outputs to nature				
Emissions to air and water from anaerobic lagoon				
Methane, biogenic	kg	5.81		
Hydrogen sulphide	kg	0.009		
Ammonia	kg	0.76		
Nitrogen oxides	kg	0.19		
Nitrogen to water	kg	1.04		
Phosphorus to water	kg	0.21		
Emissions to air and water from manure/digestate storage				
Methane, biogenic	kg	0.45	0.17	
Hydrogen sulphide	kg	0.001	0.28	
Ammonia	kg	0.36	1.30	
Nitrogen oxides	kg	0.07	0.24	
Nitrous oxide	kg	0.006		
Emissions to air and water from land application				
Ammonia	kg	0.09	0.28	0.43
Nitrogen oxides	kg	0.02	0.07	0.11
Nitrous oxide	kg	0.006	0.02	0.03
Nitrate	kg	0.54	1.71	2.49
Phosphate	kg	0.01	0.02.	0.03
Avoided emissions to air and water from mineral fertilisation				
Ammonia	kg	0.03	0.09	0.06
Nitrogen oxides	kg	0.004	0.01	0.01
Nitrous oxide	kg	0.003	0.008	0.008
Nitrate	kg	0.35	1.11	0.68
Phosphate	kg	0.01	0.02	0.03

2.3. Integration of sustainability indicators

2.3.1. The AHP method

The AHP was selected to integrate the results of the LCA with social and economic indicators since this methodology is capable of combining qualitative and quantitative indicators with multiple units of measurement. Specifically, this methodology allows evaluating the different pillars of sustainability in an integrated manner based on objective data and on the knowledge of a panel of experts.

The decision-making procedure used by AHP consists of four main steps, as defined by Saaty (2008). The first one is to define the problem and the goal of the study. Then, the criteria to be considered for decision-making should be identified. The selection of sustainable indicators is made considering which indicators better translate a comprehensive and meaningful assessment of sustainability for each specific case, according to the objective of the study. Next, the decision hierarchy is performed from the top with the goal of the decision to the bottom with the possible options, passing through the criteria and subcriteria that would be used to determine which alternative best fits the objective.

The third step is to build the pair-wise comparison matrix. This step is performed to determine the relative importance of alternatives and criteria. Each element of the matrix in the upper level should be used to compare the elements of the next lower level. These comparisons

are made on the basis of expert opinion on the relative contribution of each alternative to the different indicators, as well as on the importance of each indicator. The questionnaire distributed to experts is presented as Supplementary Material. Accordingly, in this methodology the experience and expertise of the people involved in the pair-wise comparison is as relevant as the indicators obtained. Experts are confronted with peer-to-peer comparisons; initially, they are asked to compare the importance of alternatives for each indicator and then asked about the importance of each sustainability criterion for the specific objective of the study.

The measurement scale is provided by the method and ranges from 1 to 9, as shown in Table 2. The value of 1 (equal importance) means that two indicators contribute equally to the objective of the study; while 9 (extreme importance) means that experience and judgement favour one alternative or indicator over another as much as possible. In addition, a reciprocal rating (e.g. 1/3, 1/5, 1/7, 1/9) is applied when the second indicator or alternative is preferred to the first one in the pair-wise comparison. Finally, the value 1 is always assigned to an alternative comparison itself. One of the criticisms argued to this methodology is related to the lack of mathematical basis for selecting the values of this scale.

After the pair-wise comparison, the calculation of the standard matrix is required, which is performed by dividing each number of the pairwise comparison matrix by the total sum of the column. The priority vector is then determined by estimating the average of each row in the standardised matrix. This average value for each row represents the priority vector or eigenvector of the alternative for a specific criterion. As a result, a priority matrix is developed that summarises the results of priority vectors obtained in the previous steps. It is also necessary to check consistency to ensure that judgements are consistent between comparisons by calculating the consistency ratio (CR) for each pairwise comparison. This ratio is calculated according to the consistency index which depends on the maximum eigenvalue and the number of factors in the judgement matrix. The CR of the priority vectors obtained for each criterion should not exceed 0.1, and experts should reconsider their judgements whenever a CR is higher (Wedley, 1993).

Criteria weights denote the importance of each criterion and subcriterion when synthesising the scores of the three alternatives for animal waste management (Chatzimouratidis and Pilavachi, 2009). As explained above, the pair-wise comparison criteria matrix among indicators was also estimated according to the questionnaire distributed to experts, who have assessed the relative importance of indicators. This resulted in the normalisation matrix and the priority vector.

The final step in the methodology is to use the priorities obtained from the comparisons to weigh up the different criteria and indicators. When the weighted values are obtained, they are combined with the priority matrices to determine the global priority. The result obtained is a global composite indicator that shows the relative sustainability of each alternative under study; thus, allowing the identification of the best option. This global indicator compiles the individual environmental, economic and social dimensions into a single index.

2.3.2. Selection of sustainability indicators

Since a waste management system is sustainable when it is environmentally viable, socially acceptable and economically affordable, it is essential to define environmental, social and economic criteria. The identification of an appropriate indicator for sustainable waste management should be considered representative and relevant and widely recognised in the scientific literature. The indicators selected should be able to show progress towards sustainability. To initiate the selection of relevant sub-criteria, a bibliographic review of studies dealing with multi-criteria analysis of different waste management systems was performed. Karimi et al. (2011) selected technical/administrative, economic and environmental criteria for the selection of wastewater treatment process. The environmental aspects considered odour generation, risk and sludge generation, while economic criteria entailed capital cost, land requirement, costs of operation, maintenance and sludge disposal stages. Similarly, Bottero et al. (2011) selected the use of natural resources (water and energy), noise, visual impact, odours and public opinion as environmental sub-criteria.

Regarding economic aspects, the authors assessed investment costs, public funding, operational costs and energy saving. Molinos-Senante et al. (2014) selected removal efficiencies of organic matter and nutrients, energy consumption, land requirements, as well as water and products recovery as environmental aspects. The economic indicators were investment costs as well as operation and maintenance costs, while the social indicators chosen were odour, noise, visual impact, public acceptance and complexity. Finally, Milutinović et al. (2014) selected GHG emissions, acid gases emissions, waste production as environmental sub-criteria, investment costs, operational costs and revenues as economic sub-criteria and job creation and public acceptance as social subcriteria. In this study, sub-criteria were selected considering all this information, together with the evaluations concerning animal waste management in Cyprus performed during the development of the LiveWaste project. In addition, a large number of indicators or those with high complexity may be incomprehensible, complicate the application of the methodology and make difficult to compare the different criteria and understand the results (De Feo and De Gisi, 2010). In this study, it was considered only 4 indicators to perform the analysis of each criterion. Fig. 2 shows the hierarchy tree in which all criteria and subcriteria are presented according to their importance.

As it can be observed in Fig. 2, from the 7 impact categories included in the LCA methodology a total of 4 have been considered for the sustainability assessment. More into detail, CC, TA, ME and WD were selected as they were considered relevant for analyse the environmental performance of livestock waste management systems. The quantification of impacts produced in climate change is relevant for this study since it is recognised that the management of animal waste is an important source of GHG, such as methane and nitrous oxide. Moreover, according to the European Environment Agency (2015), Cyprus is already experiencing some consequences of climate change, notably due to extensive droughts and the associated impacts on water supply and biodiversity. Similarly, marine eutrophication and terrestrial acidification were considered in this study because the impacts associated with nitrogen-based emissions are also important when it comes to manure treatment options, especially when used as organic fertiliser, as nutrient leaching is a pending problem. In more detail, marine eutrophication quantifies nitrogen leaching emissions, while terrestrial acidification is mainly related to derived ammonia emissions. Finally, due to water scarcity that Cyprus is actually facing, water depletion appears especially important since some systems are able to recover and reuse water from animal waste. Only social indicators reflecting the perception of the population were selected, as social acceptability plays a key role in the development of livestock waste treatment schemes. Employment, visual impact, odour exposure and risk perception regarding negative health effects were selected as the most important social indicators for the implementation of an animal waste management scheme. In terms of economic impacts, widely used indicators were selected that included operating and capital costs and revenues from product production.

Table 3 presents the definition of indicators for each dimension of sustainability, their direction (for a positive indicator, a higher value

Table 2
AHP measurement scale (Saaty, 1980).

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values

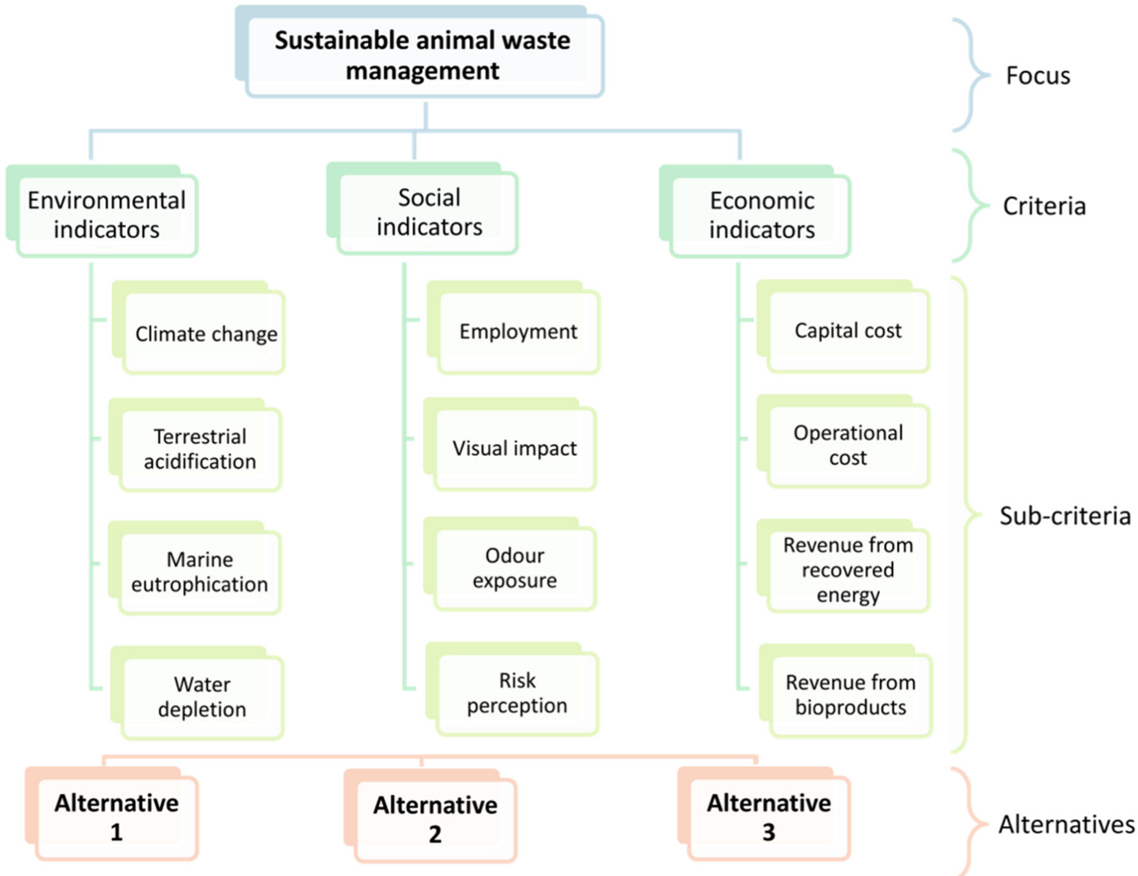

Fig. 2. The hierarchy tree for the selection of the most sustainable alternative.

represents an improvement in sustainability, while for a negative one, a higher value represents deterioration in sustainability), type of indicator (quantitative or qualitative) and the units of measurement.

2.3.3. Data collection

The data required for the quantification of the environmental indicators was specified in Section 2.2. The social aspects of livestock waste management and its impact on Cypriot resident population were evaluated by means of a multi-response survey on the basis of a previous study (Longo et al., 2016). The survey was widely distributed at the opening session of the Final Conference of the LiveWaste project. The conference was attended by hundreds of attendees, of whom only of Cypriot citizens and the main local stakeholders were able to respond to the survey, resulting in a total of 41 questionnaires. The respondents

Table 3
Criteria and sub-criteria selected to assess the sustainability of animal waste management in Cyprus.

Dimension	Indicator	Definition	Direction	Type	Unit
Environmental	Climate change	Defined as the weighted sum of the life cycle emissions of greenhouse gases, mainly carbon dioxide, methane and nitrous oxide.	Negative	Quantitative	kg CO_2 eq/t waste
	Terrestrial acidification	Related to the atmospheric deposition of acidifying inorganic substances that cause acidity change of the soil.	Negative	Quantitative	kg SO_2 eq/t waste
	Marine eutrophication	Nutrient enrichment of aquatic bodies in terms of nitrogen.	Negative	Quantitative	kg N eq/t waste
	Water depletion	It quantifies the water consumed in each of the alternatives studied.	Negative	Quantitative	m^3/t waste
Social	Employment	This indicator reflects the population perception of the potential amount of direct and indirect labour required for each livestock waste management scenario.	Negative	Qualitative	–
	Visual impact	It reflects the public perception of the visual impact of the waste treatment options.	Negative	Qualitative	–
	Odour exposure	This indicator reflects the public perception of the most common residents' complaint associated with manure management.	Positive	Qualitative	–
	Risk perception	This indicator is based on citizens' fear of adverse health effects due to the operation of the treatment schemes.	Negative	Qualitative	–
Economic	Capital cost	The investment costs of each alternative include land cost, the costs of the buildings and equipment.	Negative	Quantitative	€/t waste
	Operational cost	Includes maintenance and operational costs of each alternative.	Negative	Quantitative	€/t waste
	Revenue from recovered energy	This indicator represents the income derived from the sale of electricity from the use of biogas in a co-generation engine.	Positive	Quantitative	€/kWh
	Revenue from recovery bioproducts	This indicator is defined as the economic revenues from the sales of struvite as fertiliser and the compost as soil conditioner	Positive	Quantitative	€/t struvite and €/t compost

were mainly women (65% were women and 35% man). Of the total respondents, 50% were 5% were over 50 years, 45% between 30 and 50 and 50% under 30 years. The majority of respondents were students (45%), while the remainder worked in public administration (18%), service industry (25%) and agriculture (10%). The questionnaires were structured in four sequential stages: i) initial general questions to survey the information of the respondents; ii) specific questions concerning the perception of the current livestock waste management practices in Cyprus; iii) overview of the environmental and technical impacts demonstrated by the operation of the LiveWaste prototype; iv) specific questions related to the perception of the LiveWaste strategy to manage the livestock effluents. In this regard, respondents were asked to rate their perception of the different aspects of real waste management in their country from 1 (lowest risk) to 5 (highest risk), as well as the expected impacts after the implementation of LiveWaste technology. Specific questions included distance from houses to the treatment facilities, perception about the performance of these treatment facilities, perceived odour, perceived noise, traffic load due to livestock waste management. In other questions, they were asked to rank different animal waste treatment systems in terms of health risk perception, the most important problems perceived, the direct and indirect employment produced, the use of these effluents as fertilisers, the use of biogas, subsidies from government and expected impacts on the local economy. More information about the questionnaire can be found in Longo et al. (2016).

As far as economic indicators are concerned, the capital cost of Alternative 1 was considered the price of the land required for the anaerobic lagoon (around 10–20 €/m^2). The operational costs are related to the disposal of sludge once a year; however, they have been considered minimal. In Alternatives 2 and 3, due to a lack of information on economic aspects, bibliographic information was used. The main capital and operational costs were calculated based on published information (ERSAF, 2008; Progetto RiducaReflui, 2012) (Table 4).

3. Results and discussion

3.1. Environmental performance

This section presents the general results of the environmental impacts produced by each alternative. A sensitivity analysis of the most relevant methodological assumption to measure the strength of the environmental results obtained is also presented.

3.1.1. General environmental impacts

Table 5 shows the results obtained for the selected FU (1 t of treated manure). In addition, comparative results can be seen in Fig. 3.

As presented in Fig. 3, Alternative 1 achieved significant environmental impacts in climate change; while Alternatives 2 and 3 attained environmental benefits. More specifically, methane emissions from the anaerobic lagoon of Alternative 1 were the main contributor to these impacts, accounting for 98% of the impacts produced. Regarding Alternatives 2 and 3, the environmental benefits are linked to the production of electricity from manure, which is particularly beneficial in Cyprus due to the high proportion of fossil fuels in its electricity profile. While Alternative 2 produces electricity from manure with a well-established technology, Alternative 3 does so using more recent and advanced technologies; this also implied lower electricity consumption in Alternative 2 compared with Alternative 3, resulting in greater overall GHGs savings.

Table 5
Characterisation results corresponding to Alternatives 1, 2 and 3 per FU.

		Alternative 1	Alternative 2	Alternative 3
Climate change	(kg CO_2 eq)	202	−40.0	−22.0
Terrestrial acidification	(kg SO_2 eq)	2.48	2.52	0.240
Freshwater eutrophication	(kg P eq)	0.210	−0.001	−0.001
Marine eutrophication	(kg N eq)	1.17	0.29	0.16
Photochemical oxidant formation	(kg NMVOC)	0.344	0.236	−0.017
Water depletion	(m^3)	−0.070	−0.220	−0.41
Fossil depletion	(kg oil eq)	0.157	−15.0	−8.41

In the case of photochemical oxidant formation, the environmental impacts produced in Alternative 1 were related to direct emissions of methane and nitrogen oxides from the anaerobic lagoon and the storage and land application of manure or digestate. In Alternative 2, the most important source of nitrous oxide emissions was the storage of liquid digestate. Nevertheless, these impacts are partially reduced due to avoided electricity production. The beneficial results obtained in Alternative 3 are related to credits derived from the production of valuable products. As for fossil depletion, the environmental impacts of Alternative 1 are very low (almost negligible) compared to Alternatives 2 and 3. The reason is that this alternative has a very low level of mechanisation, which implies reduced environmental burdens associated with the production of electricity, infrastructure or diesel. In addition, the avoided electricity production from the Cypriot electricity grid resulted in environmental savings for both impact categories in Alternatives 2 and 3. Alternative 2 achieved higher environmental savings than 3 since it produces electricity from biogas with lower infrastructure and electricity requirements.

In terms of terrestrial acidification, Alternatives 1 and 2 achieved the worst environmental results due to ammonia emissions in the anaerobic lagoon and in the storage of the digestate, respectively. Finally, Alternative 3 led the best environmental results in this impact category because this treatment scheme includes the biological removal of nitrogen performed in the SBR, resulting in a lower nitrogen content in the final products, reducing the amount of ammonia emissions when applied to agricultural land.

Regarding freshwater and marine eutrophication, Alternative 1 achieved the worst environmental results due to the management of manure in anaerobic lagoons. In this practice, the nutrients contained in the manure cannot be taken by any plant and do not result in the production of any valuable product that helps to offset the environmental impacts produced. The impacts in Alternative 2 are related to phosphate and nitrate leachates from the use of digestate as an organic fertiliser. However, these impacts are partially offset by avoided emissions from the substitution of mineral fertilisers. Furthermore, phosphorus

Table 4
Average investment and operational costs for each unit process.

Unit process	Capital cost		Operational cost	
Transport	–	–	0.26	€/t waste·km
Anaerobic Digestion	3–5	k€/kW installed	0.40–0.70	€/t waste
S/L separation	80–150	k€ (10 m^3/h treatment capacity)	2.0–2.5	€/t waste
Ultrafiltration	100–200	k€ (90 m^3/h treatment capacity)	1.50–2.0	€/t waste
SBR	300–400	k€ per 30 t of waste and year	1.5–2.5	€/t waste
Struvite	–	–	0.6	€/t waste
Biogas cleaning + emission treatments	–	–	<0.02	€/t waste
Composting	400–500	k€ for 8000 m^3/year of input	0.3–0.5	€/t waste

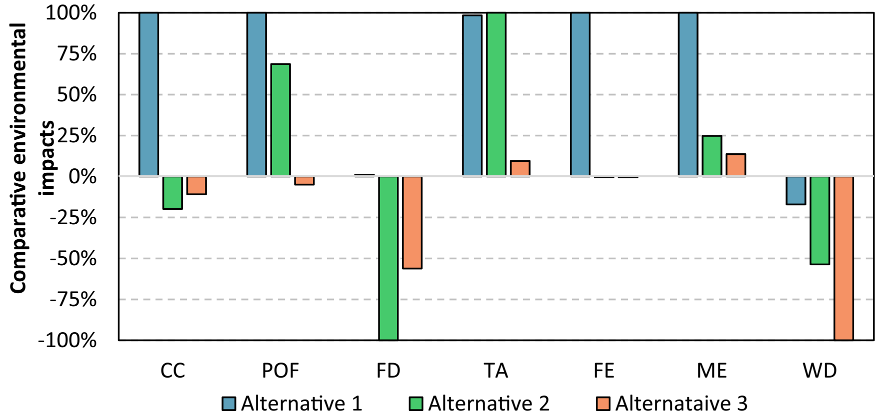

Fig. 3. Comparative environmental impacts associated with Alternatives 1, 2 and 3.

recovery and nitrogen removal in Alternative 3 also reduced the impacts of eutrophication.

The environmental results in water depletion are related to water savings due to the substitution of products such as mineral fertilisers. In addition, the production of a high quality effluent in Alternative 3 avoids the use of an equivalent amount of fresh water for irrigation.

3.1.2. Sensitivity analysis in emissions estimation

The calculation of emissions derived from the system under study is a major issue in LCA studies. In the literature, different methodologies are available for the calculation of emission from storage and spreading of organic substrates, involving different assumptions; however, methodologies that include emission factors for anaerobic lagoons are not so common.

In the base case, the IPCC (2006) methodology was applied to calculate emissions from the anaerobic lagoons, liquid and solid storage of manure and digestate, as well as from soil application of mineral and organic fertilisers (M1). As demonstrated, this methodology allows the quantification of a varied range of emissions, which is especially important when comparing a wide variety of treatment systems, as in this case. In this sensitivity analysis, the results obtained when applying this methodology were compared with those achieved using a combined methodology between the emission rates proposed by IPCC (2006) and Rotz (2004) (M2). Rotz (2004) considers that in the anaerobic lagoon 70% of total nitrogen is lost as emissions to the atmosphere, as ammonia (50%), as nitrogen gas (45%) and, unlike the other method, as nitrous oxide (5%). Regarding liquid storage, 30% loss of nitrogen as ammonia is considered. Finally, a loss of 20% is suggested for the solid storage of manure, mainly as ammonia (85%) but also as nitrate (10%) and nitrous oxide (5%). Nevertheless, in order to complete the assessment, IPCC (2006) methodology was used to calculate methane emissions from anaerobic lagoons and storage tanks, as well as emissions of nitrogen-based compounds derived from the application of mineral and organic substrates on agricultural land.

The comparative results obtained using the two methodologies to account for direct emissions are shown in Fig. 4 for each alternative.

First, it can be noted that Alternative 3 did not experience any change when using M1 or M2. The reason for these results is that in this alternative, direct emissions are only related to the application of final products on agricultural land, as this system treats all emissions on site and does not include any open storage tanks.

The use of M1 entailed greater impacts in climate change in Alternatives 1 and 2 due to nitrous oxide emissions from anaerobic lagoons and the storage of manure and digestate. On the contrary, Alternatives 1 and 2 presented a reduction of the environmental impacts produced when using M2 (from 52% to 96% of the photochemical oxidant formation impacts). The reason is related to nitrogen oxides emissions; unlike IPCC (2006), Rotz (2004) does not include emission factors for these emissions from anaerobic lagoons and storage tanks. In addition, fossil depletion also experienced reductions despite the fact that this impact category is not influenced by direct emissions from the treatment systems. In this case, lower emissions of nitrogen-compounds during the treatment process result in higher nitrogen content in the final product applied on land and, therefore, higher environmental credits from avoided fertilisation were obtained.

In the same way, the results obtained in freshwater eutrophication in Alternative 1 are the same since the impacts were produced by phosphorus emissions to water. However, differences were found in Alternative 2 for this impact category. Although the environmental burdens produced in this impact category are related to phosphate leaching from the application of organic fertilisers, these impacts were almost counteracted by avoided phosphate emissions from the application of mineral fertilisers, since the replacement value was 99%. The differences found are related to different nitrogen losses due to the different content of nitrogen in the final product that is applied on land, resulting in different amount of avoided production of mineral fertilisers. Finally, terrestrial acidification also shows a reduction when using M2 (from 7% to 27%) due to the reduction of ammonia emissions from anaerobic lagoons and digestate storage.

3.2. Sustainability performance

Each indicator was evaluated for each alternative according to the methodology explained in Section 2. The results obtained for the 12 indicators evaluated are presented in Table 6. In general, Alternative 1 had the worst results in terms of environmental indicators because anaerobic lagoons represent an important source of uncontrolled emissions of pollutants without producing any valuable product. Regarding climate change, Alternative 1 entails a significant source of direct GHG, especially due to uncontrolled emissions of methane and nitrous oxide that occurred during the anaerobic degradation of the organic matter in the anaerobic lagoon. On the contrary, Alternatives 2 and 3 achieved positive results in climate change, mainly due to the environmental credits related to the production of electricity from manure. The avoided electricity production from the Cypriot grid (highly dependent on imports of fossil fuels) was mainly responsible for these good results. Alternative 2 achieved higher environmental savings than Alternative 3 since it produces electricity from biogas with less technological development (i.e., lower requirements of infrastructure and consumption of electricity). Regarding terrestrial acidification, marine eutrophication and water depletion, Alternative 3 attained the best results due to the technology designed for nutrient management while recovering water, struvite and compost.

Concerning social indicators, the survey evaluated Cypriots' perception of animal waste management on the island. The results showed that Cypriots have been exposed to odours associated with manure

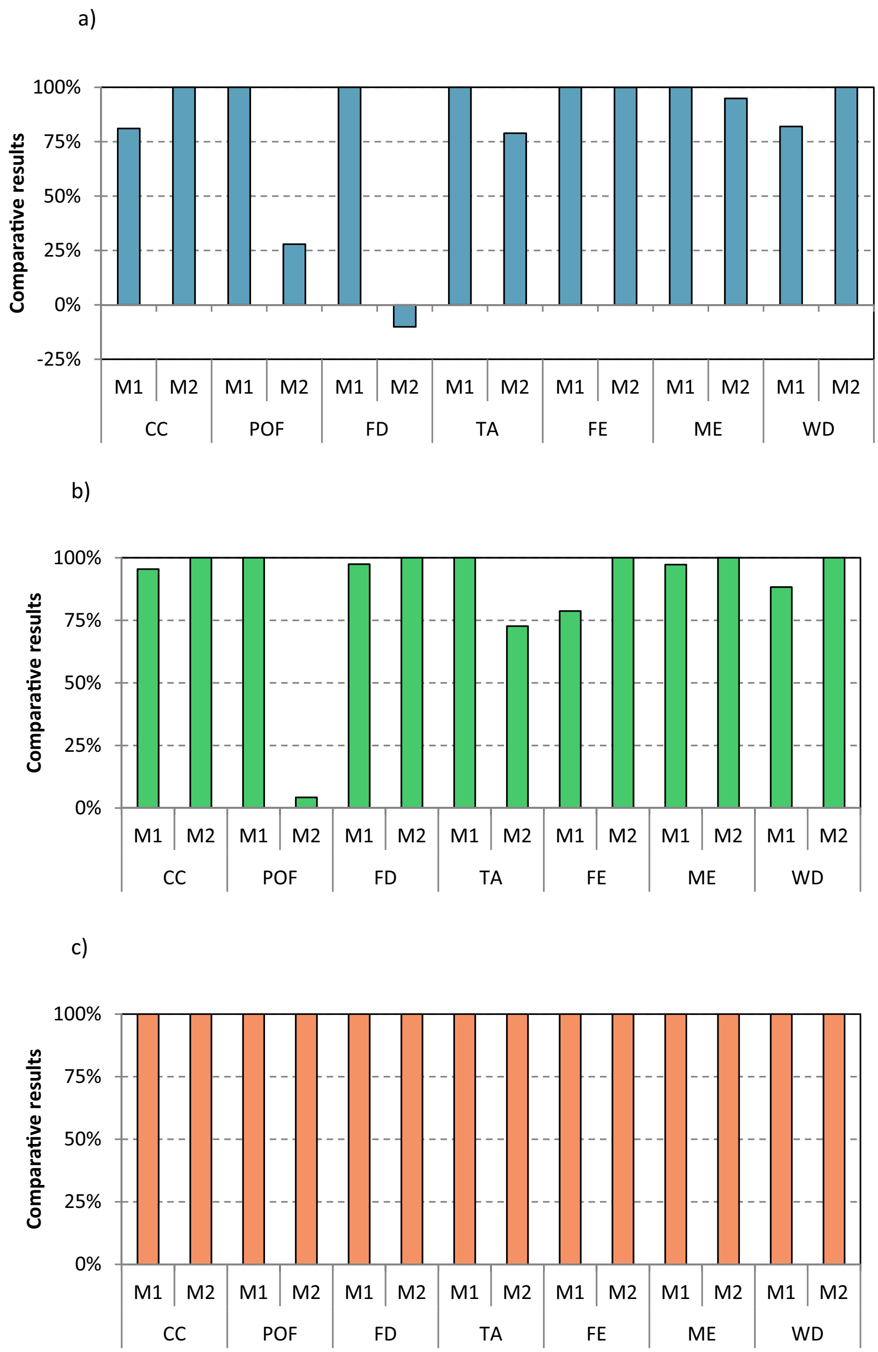

Fig. 4. Comparative results obtained for a) Alternative 1, b) Alternative 2 and c) Alternative 3 using different methodologies (M1 and M2).

disposal. Moreover, a decline could be expected due to the possible application of the LiveWaste project. The visual impact of Alternative 1 was considered high due to the area occupied by anaerobic lagoons; however, the impact was considered similar between Alternatives 2 and 3. The employment of each alternative includes the labour required to build, operate and decommission the plant. It has been considered that the operation of the LiveWaste plant may involve more employment due to the implementation of more sophisticated technology. In terms of risk perception, anaerobic lagoons were perceived, according to the survey, as the greatest source of fear regarding potentially negative effects on human health due to the associated emissions. With regard to economic indicators, Alternative 1 entails minimal capital and operational costs because of its simplicity, while not providing significant revenue. Alternative 3 was recognised as the most costly in terms of capital and operational costs since, apart from the anaerobic digestion units, it also entails other processes such as solid/liquid separation, struvite precipitation, SBR, composting and biofiltration. Nevertheless, this alternative would receive a higher income compared to Alternative 2 from the revenues of the marketable products, such as struvite and compost.

3.2.1. Pair-wise comparison and criteria weighting

The information for the pair-wise comparison was gathered through a carefully designed questionnaire that was distributed to several international experts, including master and PhD students, postdoctoral researchers and professors working in economics, psychology and environmental engineering in Cyprus, Italy and Spain.

For each indicator, experts were asked to compare the performance of each alternative according to the information provided in Table 6. Besides, they had also to rank the importance of each criterion. As an

Table 6
Results of each indicator for the alternatives under study.

Indicators		Alternative 1	Alternative 2	Alternative 3
Environmental				
Climate change	kg CO_2 eq/t waste	202	−40	−22
Terrestrial acidification	kg SO_2 eq/t waste	2.48	2.52	0.24
Marine eutrophication	kg N eq/t waste	1.17	0.29	0.16
Water depletion	m^3/t waste	−0.07	−0.22	−0.41
Social				
Odour exposure	–	High	Medium	Low
Visual impact	–	High	Medium	Medium
Employment	–	Low	Medium	Medium-high
Risk perception on human health	–	High	Low	Low
Economic				
Capital cost	€/t waste	10	66.8	71.0
Operational cost	€/t waste	~0	3.20	7.67
Revenues from energy recovery	€/kWh	–	0.135	0.135
Revenues from bioproducts	€/t struvite €/t compost	–	–	0.40 7.50

example, Table 7 shows the pairwise comparison performed by one of the experts regarding climate change, including also the priority vector and the CR obtained. According to this expert's opinion, the priority vectors obtained entail that Alternative 2 is the best in terms of climate change, while Alternative 1 showed the worst results. Due to the low inconsistency of the responses, the CR is 0.032; however, this value is considered acceptable (CR < 0.1). More information regarding the priority matrix obtained for each questionnaire as well as the maximum eigenvalue and the consistence ratio can be found in Supplementary Material.

Integrating the priority matrixes obtained for the 15 responses, the average priority matrix can be calculated. Table 8 shows the average results of each alternative for each indicator. As it can be seen, the average results obtained according to the experts' opinion are perfectly consistent with the objective information provided in Table 6. According to the results, Alternative 3 achieved the best performance (the highest rate) for most indicators; however, in terms of climate change, Alternative 2 achieved the best results while for capital and operational costs, Alternative 1 was identified as the best one.

The summary of the outcomes regarding criteria weighting is depicted in Fig. 5. As can be seen, based on the experts' opinion, for the selection of sustainable practices regarding livestock waste management, the environmental dimension of sustainability was chosen as the most relevant one (47%), followed by the social dimension (37%) and, finally, the economic one (16%). Among environmental indicators, climate change was considered the most relevant (35%), followed by water depletion (25%). Finally, terrestrial acidification and marine eutrophication achieved the same score (20%). Moreover, risk perception was identified as the most relevant social indicator (54%); while visual impact was not considered especially important compared with the rest (8%). Regarding economic indicators, revenues from energy and nutrients recovery were recognised as more significant (32% and 36%, respectively) than capital and operational costs (13% and 19%).

Table 7
Example of the pairwise comparison on climate change.

	Alternative 1	Alternative 2	Alternative 3	Priority vector
Alternative 1	1	1/9	1/8	0.055
Alternative 2	9	1	2	0.587
Alternative 3	8	½	1	0.358

Consistency ratio = 0.032.

Table 8
Priority matrix calculated.

Indicators	Alternative 1	Alternative 2	Alternative 3
Environmental			
Climate change	0.072	0.586	0.342
Terrestrial acidification	0.124	0.110	0.766
Marine eutrophication	0.069	0.369	0.562
Water depletion	0.089	0.317	0.594
Social			
Odour exposure	0.062	0.289	0.649
Employment	0.084	0.419	0.497
Social acceptance	0.086	0.317	0.597
Risk perception	0.075	0.453	0.472
Economic			
Capital cost	0.689	0.163	0.148
Operational cost	0.725	0.187	0.089
Revenues from energy recovery	0.125	0.415	0.461
Revenues from nutrients recovery	0.107	0.107	0.786

Nevertheless, it should be noted that this phase is the most subjective of the process. In this regard, a sensitivity analysis will be presented in Section 3.2.3 to identify the influence of criteria weighting on the study findings.

3.2.2. Determining the preference order of alternatives

According to the results presented in Fig. 6, Alternative 1 would be only preferred considering economic criteria, since environmental and social indicators achieved worse results compared with Alternatives 2 and 3. Moreover, Alternative 3 would be chosen over Alternative 2 taking into account environmental and social criteria. In conclusion, Alternative 3 would be the most sustainable option for the sustainable management of livestock waste in Cyprus.

3.2.3. Sensitivity analysis on the importance of relative criteria

While objective data is difficult to alter, subjective assessments can vary among decision-makers with different cultures, education and experiences. As mentioned above, to overcome this obstacle, sensitivity analysis can be used to analyse how a variation of criteria weights would affect the partial and global results (Chatzimouratidis and Pilavachi, 2009). Within this sensitivity analysis, different priorities have been given to the criteria for determining whether a change in the given weights would change the results obtained. Four different alternative scenarios (AS) were considered and the results are presented in Fig. 7.

- ✓ AS1: all criteria are equally important
- ✓ AS2: environmental factors are the most important, with an intensity of 7.
- ✓ AS3: social factors are the most important, with an intensity of 7.
- ✓ AS4: economic factors are the most important, with an intensity of 7.

As shown in the results, when the importance among environmental, social and economic criteria is the same (AS1), the economic criteria are the main contributor to the global priority vector of Alternative 1; however, for Alternatives 2 and 3 social and environmental benefits are the most relevant. The results obtained in AS1, AS2 and AS3 are comparable and Alternative 3 would be chosen, followed by Alternative 2. It is worth noting that only in the case that the economic indicators were considered the most important (AS3), Alternative 1 prevails over Alternative 2 due to lower investment and operating costs of anaerobic lagoons. In conclusion, Alternative 3 would be selected as the most appropriate alternative, regardless the relative importance of each dimension of sustainability.

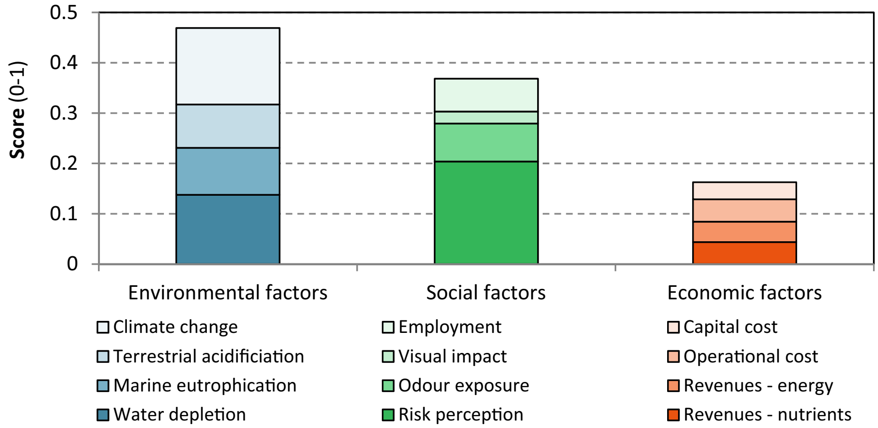

Fig. 5. Results of the criteria weighting.

3.3. Sustainable management of animal waste in other European countries

As this study demonstrates, the way livestock waste is managed can both cause environmental, social and economic impacts or can be a source of valuable products. Anaerobic digestion of livestock waste can contribute to the European efforts to develop a more circular economy aiming to achieve a sustainable, low carbon and resource-efficient economy (European Commission, 2015). The anaerobic digestion of waste streams shares the principles of the circular economy by converting this waste into several valuable products such as energy, water and nutrients.

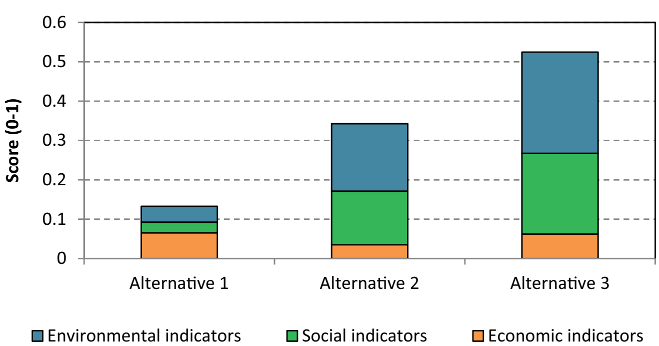

Fig. 6. Composite indicator and environmental, social and economic priority vectors for Alternative 1, 2 and 3.

More specifically, the valorisation of bioenergy from waste contributes to the achievement of European targets for renewable energy production and climate change reduction (European Parliament, 2009). The recovery of nutrients, including nitrogen and phosphorus from the digestate, is particularly interesting since the production of mineral fertilisers entails the depletion of non-renewable natural resources such as phosphate rock, oil and natural gas (Ten Hoeve et al., 2014).

Organic substrates such as animal manure or digestate have been used as fertilisers not only in Cyprus, but also in European countries to recycle their nutrients. However, related environmental impacts were detected in specific locations as a result of the current intensification and specialisation of livestock production (Oenema et al., 2007). For example, European pig production takes place mainly in eight areas: Denmark, Belgium, Netherlands, northern Germany, Brittany (France), Catalonia and Aragon (Spain) and Po Valley (Italy) (Bernet and Béline, 2009). Aiming at minimising these consequences, the application of organic fertilisers to agricultural land (both manure and digestate) is now regulated by the European Nitrate Directive 91/676/EEC (EEC, 1991). This European Directive has designed several NVZs in different European countries. These NVZs include surface freshwater and groundwater with a concentration of >50 mg/L of nitrates (EEC, 1991). In these areas, mandatory actions established to be implemented by farmers, including Codes of Good Agricultural Practice and limiting their application to 170 kg of nitrogen per hectare per year. As a result, it is sometimes necessary to transport the digestate to regions with nutrient deficits in order to redistribute it outside the intensive areas (Rehl and Müller, 2011).

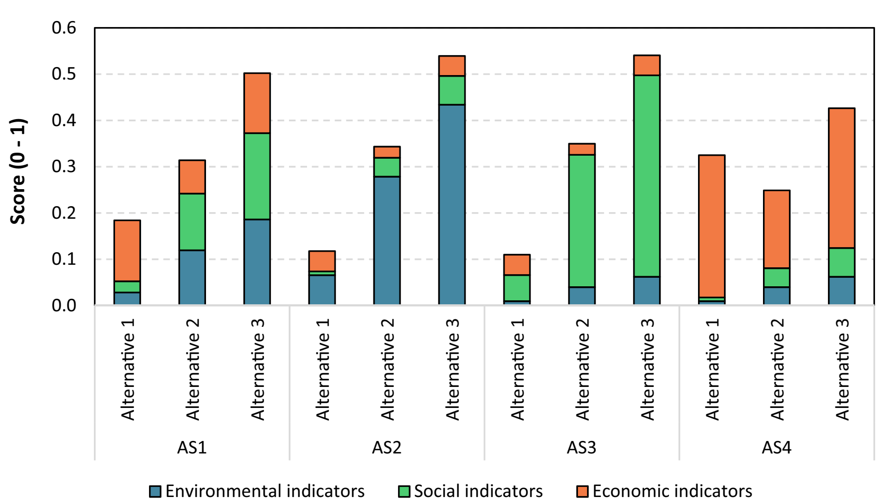

Fig. 7. Results of the sensitivity analysis.

The technology proposed in the LiveWaste project regarding digestate treatment responds to the specific demand to reduce these environmental impacts in a specific area. The degree of digestate treatment after anaerobic digestion must be in accordance to the specific characteristics of the place under study. Consequently, the application of this technology may be interesting in these European regions that are struggling due to nutrients enrichment. Agricultural land without nutritional enrichment problems could benefit from a simpler treatment scheme. Environmental and sustainability assessments are encouraged to ensure that the implementation of the selected technology conforms to the characteristics of the specific area.

4. Conclusions

This study analysed the sustainability of three options for the management of livestock waste in Cyprus. First, LCA proved to be a valuable method for providing evidence of the best treatment configuration from an environmental perspective prior to full scale implementation. Moreover, this methodology was applied in combination with AHP to compare the sustainability of different alternatives, including the management of livestock waste in anaerobic lagoons (Alternative 1), conventional biogas plant (Alternative 2) or in a facility designed according to the LiveWaste approach (Alternative 3) under environmental, social and economic indicators.

Throughout the application of the methodology, each indicator selected was analysed individually. This step shed light on the advantages and disadvantages of each alternative. Alternative 1 was identified as the worst alternative from an environmental (e.g. 202 kg CO_2 eq, 2.48 kg SO_2 eq and 1.17 kg N eq per tonne of waste) and social point of view (high impacts in odour expose and visual impact), mainly due to the uncontrolled emissions of pollutants. However, it is the one with the lowest capital and operating costs. The high technological development of Alternative 3 (in comparison with Alternative 2), which performs the removal/recovery of nutrients, entailed greater impacts on some environmental and economic indicators, such as climate change and operating costs (which were close to 50% higher), while reducing impacts on other indicators such as terrestrial acidification and marine eutrophication (which were found to be 10 and 2 times lower) and revenues from energy and nutrients recovery. The following steps of the methodology are applied according to the opinion of a panel of experts. According to the results, although the capital and operational costs of Alternative 3 are higher, the environmental, social and economic benefits derived from the recovery of products made it the most sustainable option for animal waste management. Alternative 2 was selected as the second preferred option. However, this process entails a higher level of subjectivity, especially in the weighting of criteria. Therefore, a sensitivity analysis was needed to analyse the influence of criteria weighting on the results. Although Alternative 3 was in all cases the most sustainable option, when economic criteria are the most weighed dimension, Alternative 1 can be selected over Alternative 2.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.03.299.

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